BELLCOMM, INC.

1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Benefits Achieved by Throttling the DPS in the High-Thrust, Fixed Throttle Position to Produce a Predictable Thrust Profile - Case 310

DATE: April 26, 1968

FROM: G. L. Bush

ABSTRACT

Effects of thrust uncertainty in the fixed throttle setting portion of the LM descent braking phase are discussed. Because of engine thrust uncertainties, present LM descent mission planning imposes a ΔV penalty of 100 ft/sec, a limitation of 1 degree downhill approach slopes, and an added complication to the crew's monitoring of descent parameters.

Conclusions reached here are that those penalties described above can be greatly reduced by throttling the engine in the high-thrust Fixed Thrust Position to produce a reproducible thrust profile. By so doing a 100 ft/sec ΔV saving could be achieved; downhill slopes of up to 2 degrees could be tolerated; and the crew's ability to recognize off-nominal performance would be enhanced.

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MEMORANDUM FOR FILE

The braking phase portion of the LM descent is flown with the Descent Engine (DPS) throttled to a fixed position for about 380 seconds of the phase. This constraint insures that the engine is not throttled between 60 and 90% of maximum thrust, a region of excessive erosion. The guidance system satisfies the fixed throttle constraint while achieving high-gate conditions of position and velocity. This is done by directing the engine thrust along the direction commanded by the guidance equations but leaving the throttle set to 92.5% maximum thrust. When the magnitude of the commanded thrust falls to 52% maximum thrust, control is established over the throttle, and the commanded thrust is achieved for the rest of the flight. Figure 1 shows this effect by plotting actual and commanded thrust vs. time. Command direction of thrust is achieved over the entire phase.

When the throttle is placed at 92.5% of maximum thrust, there is an uncertainty as to the actual thrust that will result. Figure 2 shows this effect. Because of this uncertainty, the present LM descent planning calls for the braking phase to be targeted to take this into account. The trajectory is designed to insure at least 30 seconds of thrust level control for the worst (low) engine performance case. Uncertainty in high-thrust profile produces disadvantages for the LM descent. These are now described.

A. Fuel Cost

In order to insure at least 30 seconds of thrust level control for the low thrust engine performance (3σ = 3% low), the braking phase is designed so that a nominal engine thrust performance will cause control over the throttle to be re-established 120 seconds before the end of the phase. This is costly in fuel:

a. The ΔV penalty for moving the nominal-trajectory throttle down time back from 30 seconds before high-gate conditions is about 1 $\frac{\text{ft/sec}}{\text{second}}$ (1). This number applies to thrust-acceleration deviations in the range 2-4% and throttle-down times of 70-160 seconds prior to high-gate conditions. For a 120 second throttle down time rather than a 30 second throttle down time, the ΔV penalty is about 90 ft/sec.

b. A high-thrust engine will throttle down prior to the 120 second nominal. For a $(+3\sigma = +3\%)$ high thrust engine, the throttle down time is approximately 150 seconds. The ΔV cost for an earlier throttling-down time is about 1 $\frac{\text{ft/sec}}{\text{second}}$. Thus descent ΔV budget must allow for this possibility as a contingency and the budgeted ΔV is about 30 ft/sec.

Thus the Fixed Throttle Position (FTP) thrust uncertainty imposes a penalty of about 100 ft/sec.

B. Allowable Downhill Slopes

Downhill slopes cause guidance system problems for the following reason. When the LM's estimated altitude reaches 25,000 feet, the landing radar's estimate of altitude is combined with the IMU's estimate of altitude to produce a better estimate. For the case of downhill slopes, the radar will measure the altitude to be less than that estimated by the IMU; and as updating proceeds, the Guidance System's estimate of altitude soon is lower than it would have been had there been no radar update. The guidance system responds to this lower than nominal altitude by pitching closer to the vertical. This causes the velocity beams to approach closer to being perpendicular to the vehicle's velocity vector or closer to a zero-doppler condition. Altitude data is dependent on proper radar velocity operation to account for the doppler-shift of the altitude (range) beam. If the zero-doppler condition occurs, radar altitude updates stop, and a time lag occurs before radar update begins again. If a downhill slope caused zero-doppler loss of velocity correction, it is likely that loss will occur again for the same reasons. Thus allowable downhill slopes are determined by insuring that the probability that the zero-doppler condition is small.

The uncertainty of engine thrust in the fixed-thrust portion of the braking phase increases the probability that when flying over a given slope, zero-doppler drop-out will occur.[2] Figure 3 shows this effect.* The ordinate of Figure 3 plots the probability that the minimum range beam incidence angle is less than nine degrees. Reference 2 describes the significance of nine degrees as being a limiting angle for the zero-doppler condition. If the vehicle were to pitch nearer the local vertical making the range beam incidence angle become less than nine degrees during the braking phase, zero-doppler is likely to occur. The abscissa of Figure 3 is slope in degrees. Greater downhill slopes increase the probability that the minimum range beam incidence angle is less than nine degrees.

Figure 3 shows that the probability that the zero-doppler boundary (9°) is exceeded when the terrain is a downhill slope of one degree is about .25 for a 2% High Thrust Engine. For the same slope and a nominal or low thrust engine, there is little probability that zero-doppler drop-out will occur. For a downhill slope of two degrees, only the low thrust case has a low probability of exceeding the zero-doppler boundary. The probability that the boundary is exceeded for the +2% high-thrust case flying over a two degree downhill slope is about .9.

Because of the thrust uncertainty, landing sites should be selected which have less than one degree downhill slopes.** However, since Lunar Orbiter Data is used, mapping of landing sites can only determine slopes to ± 1°. This mapping uncertainty, essentially limits approach terrains to those having flat or uphill slopes.

Thus the FTP thrust uncertainty imposes a penalty to mission planning in that only sites of approximately flat (or at most one degree downhill slope) terrain. If the FTP thrust could be controlled (say to a nominal thrust profile), the braking phase could be targeted so that throttle control is regained 30 seconds before high-gate. Probability of zero-doppler drop-out would be essentially like the -2% low thrust case shown in Figure 3. It appears that slopes up to 2 degrees (downhill) could be tolerated without violating the zero-doppler region.

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*Figure 3 was derived from Monte-Carlo Simulations of the LM guidance and navigation systems over general downhill slopes from the landing site. Altitude updates were assumed to commence at 25,000 feet. A nominal thrust trajectory produced throttle down at T_{go} = 120; altitude = 22,000 feet.

**Reference 4 suggests that general downhill slopes of 2° can be tolerated.

C. Crew Monitoring and Safety

During the powered descent, the crew will monitor their flight by comparing flight parameters to nominal flight parameters. Nominal flight parameters of necessity will have to be produced from a simulation of the descent using a nominal thrust engine. If during the actual flight, a high or low thrust developed, the flight parameters such as h vs $\dot{h}$, h vs R_{go}, and γ vs v would naturally vary from nominal. The astronauts would have some uncertainty as to the cause of the off-nominal trajectory. If some other performance malfunction were causing the off-nominal performance (e.g., a slowly drifting platform), the crew will have to wait until the flight progresses to ascertain whether the engine is off-nominal or if something else is wrong. Eliminating a source of uncertainty and aborting without delay (when a problem is recognized) is advantageous from a crew safety standpoint.

Throttling the Engine in the FTP

It seems probable[3] that the engine can be safely throttled in the high-thrust region by as much as ± 3%. Since expected thrust variations are ± 3%, a simple feedback scheme can be devised to throttle the engine so that a predictable fixed thrust can be achieved. Some impact would be imposed in a software method to do the throttling. Little hardware impact would be imposed. The braking phase trajectory can be targeted using the predictable fixed thrust profile.

Conclusions

From the viewpoint of fuel savings, site selection, and crew safety, the conclusion is reached that throttling the engine in the high thrust, fixed thrust region should be implemented. The ΔV savings would be approximately 100 ft/sec. Downhill slopes of up to 2° could be tolerated (rather than the present 1° slope). The crew could more safely monitor the braking phase portion of the flight with a predictable high thrust.

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4. Lunar Landing Site Selection Briefing, LM Guidance System Constraints Affecting Landing Site and Approach to Landing Site, Cheatham, D. C., March 8, 1967.

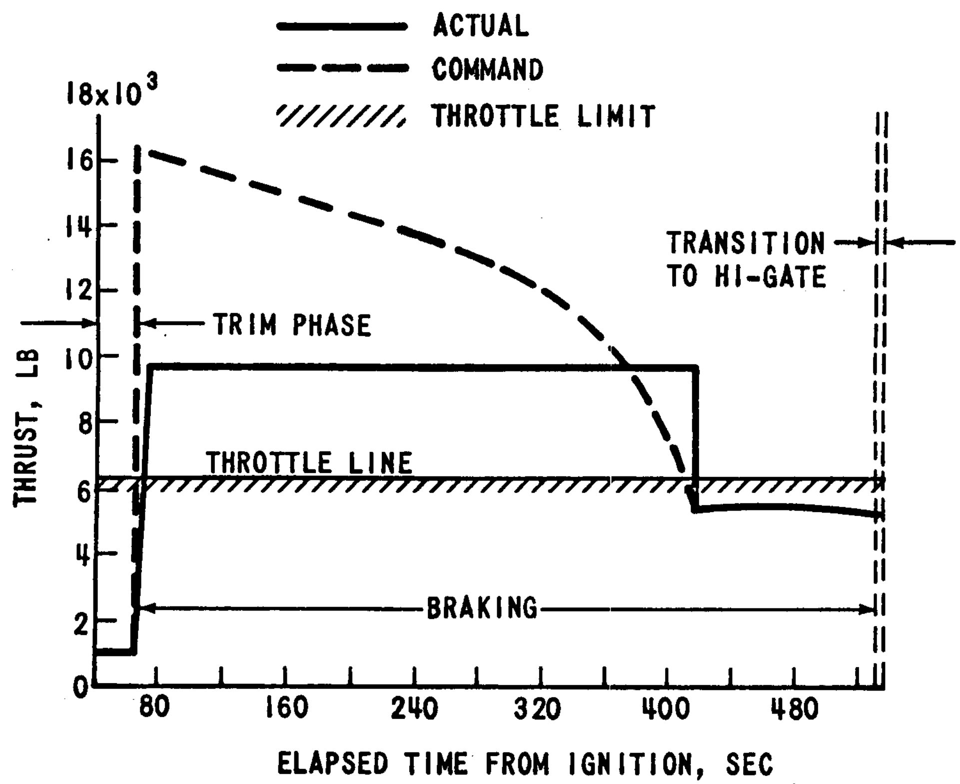

FIGURE 1 - TIME HISTORIES OF POWERED DESCENT

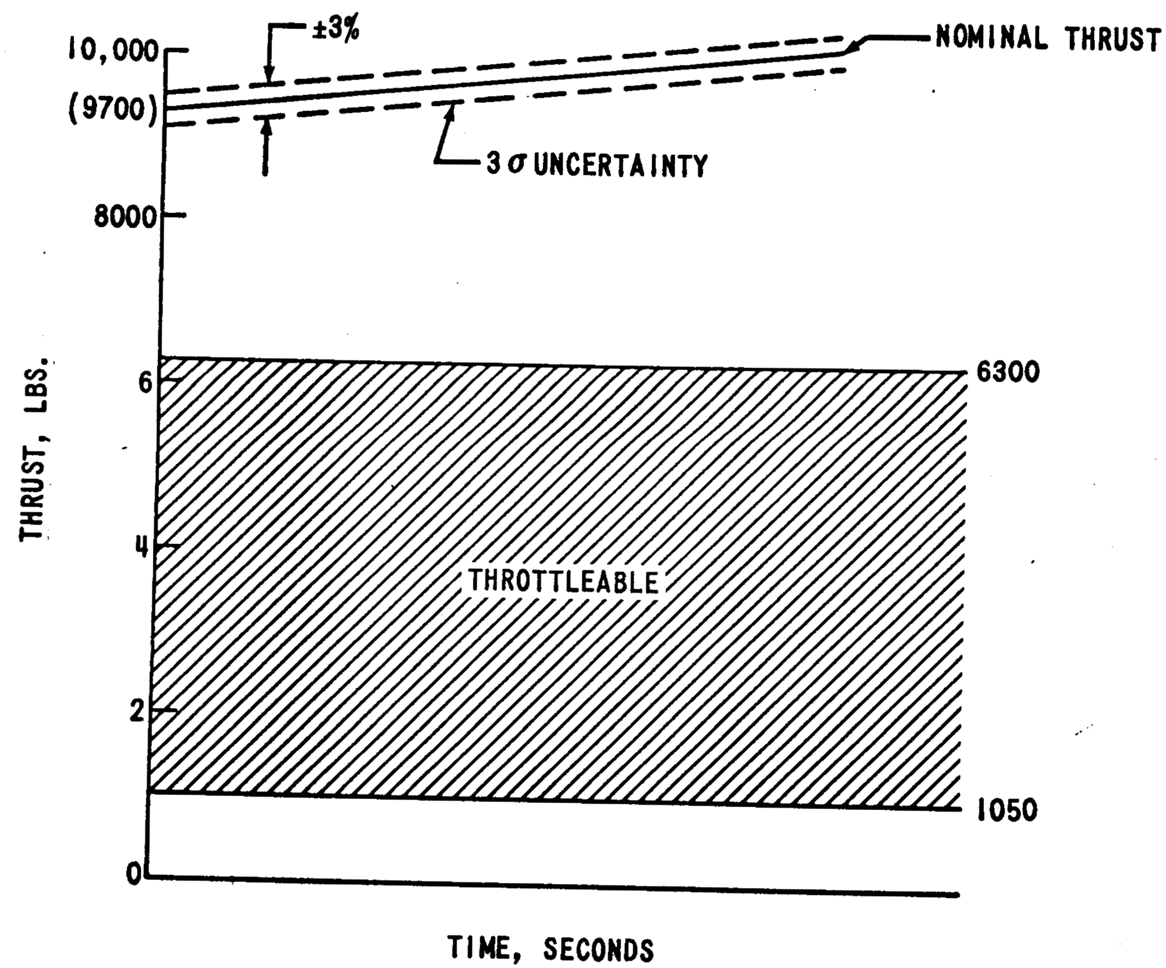

FIGURE 2 - LM DESCENT ENGINE THRUST CHARACTERISTICS

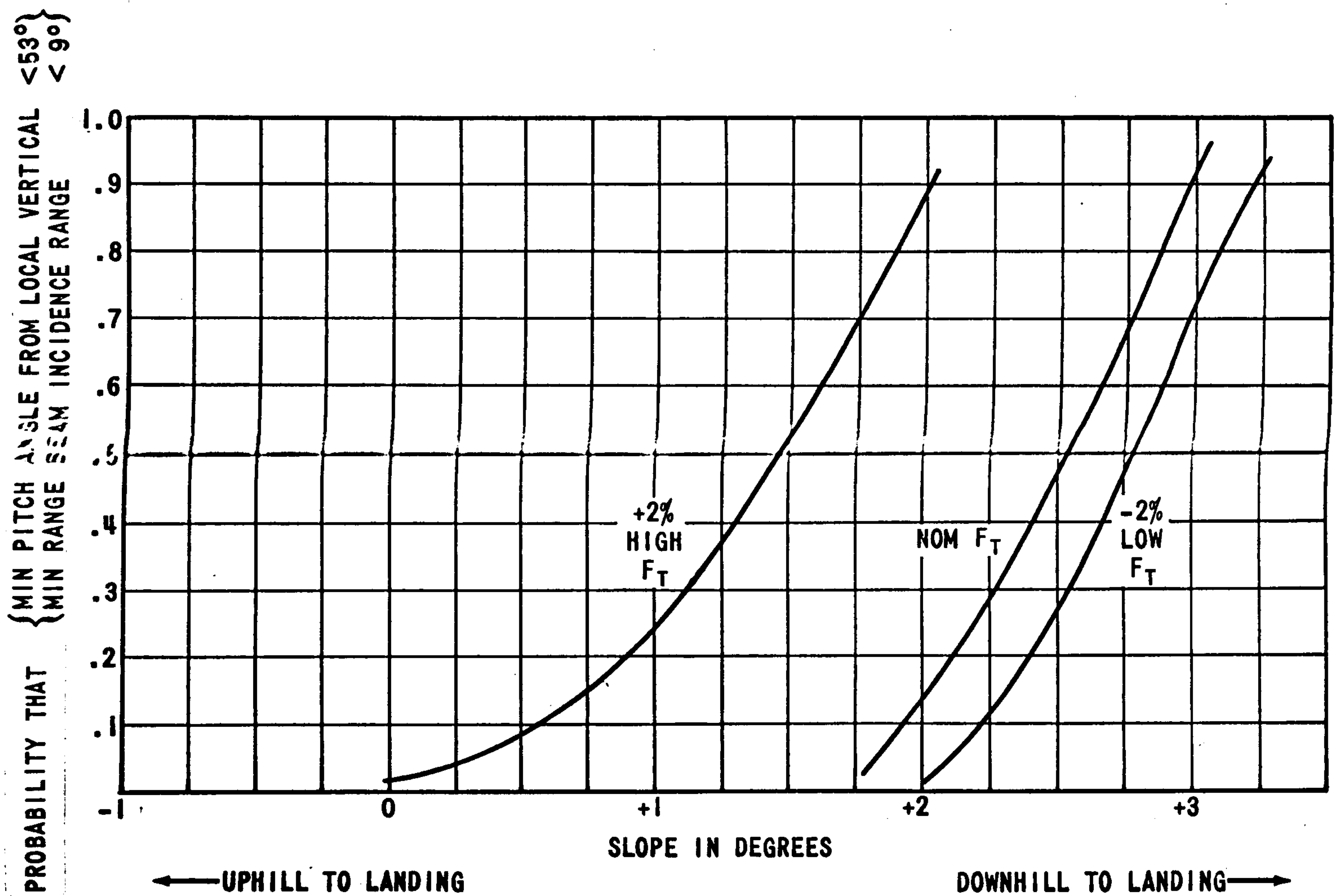
PROBABILITY THAT {MIN PITCH ANGLE FROM LOCAL VERTICAL <53°}
{MIN RANGE BEAM INCIDENCE RANGE < 9°}
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-1
0
+1
+2
+3
+2% HIGH F_T
NOM F_T
-2% LOW F_T
SLOPE IN DEGREES
UPHILL TO LANDING
DOWNHILL TO LANDING

FIGURE 3

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